Field Trip Notes, June 24, 2000
Geologic Controls on Select Springs near Flagstaff, Arizona
Planetary Geologic Mappers Meeting, Flagstaff, Arizona
June 22-24, 2000

INTRODUCTION

Volcanic rocks, unconsolidated rocks, sandstone, siltstone, and limestone that are Recent to Permian in age underlie the greater Flagstaff area and contain several perched aquifers and a regional aquifer. Geologic structure increases the complexity of the aquifer characteristics and ground-water flow systems in the Flagstaff area and is the main control on the occurrence and location of most springs in the area.

Recent evidence of young landforms on Mars, seen in high-resolution images acquired since March 1999, suggest the presence of sources of water at shallow depths beneath the martian surface. All of these landforms display geomorphic features that can be explained by processes associated with ground-water discharge and surface runoff. Geomorphic features associated with spring areas of the southern Colorado Plateau in Arizona are similar to some of the geomorphic features seen on Mars. This field trip was organized to observe select springs in the Flagstaff area that show a variety of landforms, geomorphic processes, and structural controls, in a terrestrial setting, that may be analogous to similar features seen in the martian images. Photographs of select springs at the west end of the Grand Canyon also are included. In figure 1 a series of sketches show the general geologic and structural relations of principal spring types.

REGIONAL SETTING

The Flagstaff area is on the south edge of the Colorado Plateau at an elevation of about 7,000 ft (2,134 m) and receives annual precipitation of about 22 inches (559 mm); thus the region is classified as semi-arid. At higher elevations on the nearby mountains annual precipitation is as high as 35 inches (890 mm). Highly permeable, cindery soil and fractured rocks generally allow precipitation to percolate to great depths. For this reason, perennial streams are absent in the immediate area.

Flagstaff and the surrounding area overlie a complex series of volcanic and sedimentary rocks (fig. 2). These rock formations are deformed locally and regionally by a series of folds and fractures that collectively define the geologic structure of the area (fig. 3). This structure partly controls the occurrence and movement of ground water. Ground water in some areas is perched close to land surface by dense and unfractured volcanic rocks or by fine-grained sediments and sedimentary rocks. Ground water also occurs throughout the area in sedimentary rocks deep in the subsurface in a regional aquifer. This regional aquifer is the source of water for many springs along the south rim of the Grand Canyon and the source of springs and perennial flow in tributaries to the Verde River to the south.

Perched Aquifers

In some areas near Flagstaff, ground water is ten's to less than 300 ft (2 to 91 m) below land surface in fine- to coarse-grained volcanic rocks, sediments, or sedimentary rocks. These water-bearing zones supply many of the seeps and springs in the Flagstaff area. They occur in a variety of environments that are represented by one or more types of geomorphic and structural controls.

Regional Aquifer

Ground water also occurs in the sedimentary rocks that underlie the entire area. These water-bearing zones are recharged by precipitation and runoff that percolates deep into the subsurface. Fracturing associated with structural deformation increases recharge locally. Ground water in this regional aquifer moves laterally and vertically until it discharges as springs in deeply incised canyons to the north and south. These canyons are developed along regional structural trends that have been exploited by ground-water flow and surface runoff.

FIELD TRIP STOPS

The locations of field trip stops are shown on figure 4.

Stop 1: Coyote Spring (fig. 5).

One of several springs in this area, Coyote Spring has about 5 gal/min (0.31 L/s) perennial flow and is an unconfined, perched, fracture and contact spring. The developed spring issues from fractured basalt (Pliocene to Miocene in age) overlying Moenkopi Formation (mid-lower Triassic in age) on the west side of Switzer Mesa next to U.S. Hwy 89A and the Museum of Northern Arizona. The fracturing in this basalt flow is from differential stress as the flow cooled. Also, a northwest-trending fault runs parallel to the west side of Switzer Mesa. The upthrown block to the east and south probably contributes to Coyote Spring and other springs in this area by restricting ground-water flow across the fault plane. A debris apron of fine silt deposited by the spring is visible downstream and is overgrown with vegetation.

Stop 2: (optional) Tunnel Spring.

Tunnel Spring is an ephemeral, unconfined, perched fracture and contact spring. The spring is north of the railroad tracks behind the new Railroad Springs development. Undeveloped, the spring flows downstream into a stock tank constructed to catch flow. The spring issues from the upstream end of an enlarged and incised channel in fractured basalt (Pleistocene in age) on top of an older basalt flow (Pliocene to Miocene in age) at the south end of Observatory Mesa. The spring is currently dry owing to the dry conditions this year. Mounds of raised silt on both sides of the channel are densely vegetated and may represent old secondary seeps. Tunnel Spring is typical of several springs that issue from fractured basalt at the base of Observatory Mesa. Water from these springs only flows for short distances at land surface before it is evapotranspired back to the atmosphere or infiltrates into underlying rock units

Stop 3: Turnout, Lake Mary Pumping Station (fig. 6).

The turnout at the Lake Mary Pumping Station offers views of Lake Mary graben, Anderson Mesa, and Lake Mary faults. These regional geologic structures have a major influence on the occurrence and movement of ground water in the regional aquifer in this area. Lake Mary graben is the downdropped block between the Anderson Mesa fault to the north and Lake Mary fault to the south. Upper Lake Mary and Lower Lake Mary, within the Lake

Mary graben, are man-made lakes and store runoff from the drainage upstream. No springs feed the lakes owing to the offsets of the faults and fracturing associated with the faults, which enhances the infiltration of water deep into the subsurface. The depth to water in the regional aquifer in this area is about 350 ft (107 m) below land surface as indicated by the static water level in well LM-4 about 300 ft (91 m) to the south of the pumping station. Local drawdown when the city of Flagstaff wells are pumping can be an additional several hundred feet (150 to 200 m). Recovery when the wells are off, however, is rapid. The Anderson Mesa fault is uplifted several hundred feet to the north (about 150 m). The Lake Mary fault is uplifted 50 to 100 ft (15 to 30 m) to the south. Just to the east and south of the turnout (center and right of photograph) in Lower Lake Mary and behind the coffer dam are several small depressions and openings. These features have developed directly over fractures in the Kaibab Formation that have been widened over time by dissolution and erosion of the rock.

Stop 4: Clark Spring.

Clark Spring issues from fractured Kaibab Formation (lower Permian in age) at the base of slopes and where the drainage intersects the water table in the regional aquifer. The spring is a perennial, unconfined, regional aquifer spring controlled by fractures in the Kaibab Formation and by subregional northeast- and northwest-trending faults. The channel below the spring is incised into alluvium and bedrock, and the drainage is significantly wider just downstream of the spring. Overall the drainage is constrained by northeast-trending geologic structure. Although Clark Spring is dry this visit, the site typically has a flow of 20-40 gal/min (1.26 to 2.54 L/s). Clark Well, hand dug into alluvium and Kaibab Formation about 1,000 ft (305 m) downstream, currently has a water level about 5 ft below land surface. During more normal years Clark Well also flows at land surface. The current dry conditions are likely due to a combination of drought and City of Flagstaff water use.

Stop 5: Hoxworth Springs.

Hoxworth Springs issue from the contact with old basalts (Pliocene to Miocene in age) at the upstream end of the reach and from fractured Kaibab Formation at the downstream end of the reach where these rocks are exposed at land surface. The springs are perennial, confined regional aquifer springs controlled by formation contacts and fractures. Some flow in the upper reach is from water perched in fractures in the basalt rocks. The basalt flows, however, mostly confine water in the Kaibab Formation in this area. During this visit, the lower reach where water typically flows from the Kaibab Formation was dry, except for a few areas of ponded water. First flow is at the middle pool where water issues from the basalt/Kaibab Formation contact. Flow here is about 1-2 gal/min (0.12 L/s) and increases upstream to about 10 gal/min (0.63 L/s). Note that the drainage upstream of the springs is very narrow. At the springs the drainage expands to a large flat valley of alluvial material overlying bedrock with the main channel downstream of the springs being incised into the alluvium and bedrock.

Stop 6: Un-named spring adjacent to I-17 just north of Kachina Village (fig. 7).

With 2 outlets, the un-named spring issues from large fractures in the base of a dense basalt flow (Pleistocene in age). The spring is perennial (20-40 gal/min; 1.26-2.52 L/s), unconfined, perched, and controlled by fracture in basalt. Two small alcoves with incised channels and weak sapping of the overlying basalt have developed at the head of the spring area. This un-named spring is at the north end of the Munds Park graben on the upthrown side of one of the bounding faults. Directly opposite this spring on the east side of I-17 the Kaibab Formation is exposed at land surface. The depth to water in the regional aquifer in this area is about 1,200 ft (366 m) below land surface.

Stop 7: O'Neil Spring.

O'Neil Spring issued from a contact between fractured basalt and dense basalt in a well-developed ravine. There is no direct access to this site but it is visible from the frontage road between the freeway and Kachina Village to the south. The spring is perennial, unconfined, perched, and controlled by contact between basalt flows and fractures in the basalt. The perennial flow of this spring contributes most of the water to the wetland at Kachina Village just downstream. O'Neal Spring has a developed headwall with sapping of overlying basalt. The channel below the spring flows out of the ravine incised into a small distributary flow apron of material eroded from the ravine. There is no significant drainage upstream of the spring.

Stop 8: Griffiths Spring.

Griffiths Spring has two outlets that issue from fractured basalt (Pleistocene in age). Both of these outlets have well developed debris fans and incised channels. The spring is ephemeral, unconfined, perched, and controlled by fractures in basalt. Griffiths Spring is on State highway 89A just south of Fort Tuthill. Lindergh Spring, about 0.75 mi. south on 89A, is similar to Griffiths Spring except it has perennial flow. The spring area use to be a rest stop on 89A and is currently fenced off to facilitate redevelopment of the original vegetation and wetland.

Stop 9: Oak Creek Canyon Overlook (fig. 8).

The Oak Creek Canyon overlook provides views of Oak Creek and the Oak Creek fault. The fault is upthrown to the west about 500 ft (152 m) at this point and records both Laramide compression and more recent Basin and Range extension. This has implications for the occurrence and movement of water in the regional aquifer, because compressional faults are typically closed and impede the flow of water across the fault plane and extensional faults are more open allowing water to flow more freely across the fault plane and down the fault. All of the springs in Oak Creek Canyon occur on the west or upthrown side of Oak Creek fault. The perennial flow of Oak Creek is spring fed beginning at Sterling Spring at the base of the switchbacks on 89A. Sterling Spring issues from the very fractured Coconino Sandstone (lower Permian in age) where the fault plane intersects the water table in a short, very steep tributary canyon. The spring is perennial, flowing at about 300 to 400 gal/min (18.9 to 25.2 L/s), unconfined, and controlled by Oak Creek fault. Pumphouse Wash, the much larger and more developed drainage to the east on the downthrown side of the fault, is dry except for seasonal runoff.

Stop 10: Call of the Canyon and West Fork Springs (fig. 9).

Just upstream on the West Fork of Oak Creek are several un-named springs that issue from the Coconino Sandstone by seepage through pore spaces in the rock and from fractures associated with the Oak Creek fault. The flow in West Fork at this point is about 500 to 600 gal/min (31.5 to 37.9 L/s). The West Fork of Oak Creek has incised a channel below the regional water table in this area. Springs in this area are characterized by two different geologic processes. Some springs are broad seeps and seepage faces that cover several hundred square feet (a hundred or more square meters) and are characterized by flat to overhung seepage faces with hanging gardens and where rock spalls from the seepage face in small to large sheets. These types of springs and seeps are identical to the sapping springs and features described by Howard and others (1988) and are the result of the main channel having rapidly incised bedrock to well below the regional water table. In some areas spring flow is concentrated to a point by fracturing in the rock caused by the Oak Creek fault. Horizontal and vertical to near vertical feeder fractures can be seen in the rock face concentrating flow to a single fracture that has been further widened by dissolution and erosion of the rock by the concentrated flow.

Select Regional Aquifer Springs at the West End of the Grand Canyon

Clay Spring (fig. 10).

Clay Spring is controlled by a near vertical fault in the Muav Limestone (Cambrian age) that parallels the north side of an east-west canyon in the Grand Wash Cliffs at the west end of the Grand Canyon. The spring is perennial and unconfined. The scarp is clearly visible as a line running nearly horizontal across the middle of the photograph. The spring is at the left center of the photograph marked by the increase in surrounding vegetation. The drainage upstream of the spring and the fault are poorly defined. At the fault and spring the drainage becomes a series of three well-defined channels that combine into one larger channel at the bottom of the photograph. This spring correlates well to features seen in recent Mars Orbiter Camera images.

New Water Spring (fig. 11).

New Water Spring is controlled by solution-widened fractures in the Muav Limestone (Cambrian age) associated with the north-northwest-trending Rampart Cave fault. A north-northwest-trending drainage has developed along the fault on the Grand Wash Cliffs at the west end of the Grand Canyon. The spring is perennial and unconfined. The spring is marked by a semi-circular area of collapse on the west side of the canyon with small trees and brush defining the perimeter. The main channel below the spring is about twice as large as above with two distinct branches.

Quartermaster Spring (fig. 12).

Quartermaster Spring is controlled by solution-widened fractures in the Muav Limestone and contact with the underlying Bright Angle Shale (Cambrian age). The spring is perennial and unconfined. Spring flow varies seasonally from about 450 to more than 15,000 gal/min (28.4 to 946 L/s). The current outlet for Quartermaster Spring is from a depression on top of a travertine mound on the northwest edge of a much larger, older travertine mound. In both cases these spring outlets and travertine mounds have developed near the contact with the Bright Angle Shale. The Bright Angle Shale is very fine grained siltstone and shale and is the lower confining layer for ground-water flow in the limestone aquifers in this part of the Grand Canyon. Quartermaster Spring is still actively depositing travertine, and the deposits have dammed the drainage resulting in over 600 ft of alluvial fill in the drainage upstream of the spring and a waterfall to the Colorado River downstream of the spring.

Boundary Spring (fig. 13).

Boundary Spring is controlled by the contact between the Muav Limestone and the underlying Bright Angle Shale. The spring issues from the base of Muav Limestone cliffs through solution-widened fractures in the limestone. The active part of the spring is visible in the upper right of the photograph and is marked by dense vegetation. Older, currently dry, outlets are visible in the middle of the photograph and are marked by well-defined, deeply incised channels in the talus and colluvium that have little or no relation to poorly defined drainage above the limestone cliffs. Another discharge point is noted in the left center of the photograph where still active seeps support moderate to thick vegetation at and downstream of the cliff face. In addition this area has the beginnings of an alcove type structure that appears to be eroding back to the headwall seeps. Although this feature could be due more to erosion from surface runoff in the main channel the constant presence of moisture provided by the seep probably is an agent in weakening the rock and thus facilitating its erosion. The geomorphic features of Boundary Spring are very similar to features seen in the recent Mars Orbiter Camera images.

Figure 1. Sketches showing the different types of springs.

Figure 2. Generalized stratigraphic section of rock units, Flagstaff, Arizona.

Figure 3. Landsat Thematic Mapper image, June 22, 1991, Flagstaff, Arizona (from Chavez and others, 1997).

Figure 4. Map of the Flagstaff area showing field trip stops.

Figure 5. Photograph showing Coyote Spring.

Figure 6. Photograph showing turnout, Lake Mary Pumping Station.

Figure 7. Photograph showing un-named spring adjacent to I-17 near Kachina Village.

Figure 8. Photograph showing Oak Creek Canyon overlook.

Figure 9. Photograph showing Call-of-the-Canyon and West Fork Springs.

Figure 10. Photograph showing Clay Spring.

Figure 11. Photograph showing New Water Spring.

Figure 12. Photograph showing Quartermaster Spring.

Figure 13. Photograph showing Boundary Spring.